An ADTRAN White Paper

Defining Broadband Speeds: Deriving Required Capacity in Access Networks

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Executive Summary

As part of the Federal Communications Commission's work in developing the National Broadband Plan, the FCC has sought comments on a number of subjects related to broadband access. In NBP Public Notice # 1 [1], the FCC sought comments regarding the definition of broadband. ADTRAN, in responding to that request, referenced a previous White Paper [2] in which the definition of broadband was linked to capacity in the access network.

More recently, the FCC has sought comments (in NBP Public Notice # 11 [3]) regarding middle and second mile access, including the amount of second-mile and middle-mile capacity required to provide adequate broadband Internet access to the end users of the network. This White Paper directly addresses that question and expands on the relationship between capacity and the speed experienced by users in access networks. The paper discusses the importance of sustainable speed as experienced by the user – as opposed to other definitions such as peak or advertised speed – to a number of widely used application classes. It then addresses the relationship between capacity and demand that enables sustainable speeds on the access network.

The paper also provides updated projections for traffic demand and required capacity, based on new estimates and projections in Cisco's Visual Networking Index [4, 5]. The traffic volumes provided in the index are converted to estimates of per-household traffic, with scaling added to account for diurnal patterns. The average traffic is then scaled to account for non-uniform usage distributions and self-similar traffic distributions, resulting in per-user capacity requirements. The data generated from the 2009 VNI shows growth rates for North American consumer Internet traffic that are significantly higher than the corresponding rates from last year's source data.

1 Introduction

As part of the Federal Communications Commission's work in developing the National Broadband Plan, the FCC has sought comments on a number of subjects related to broadband access. In NBP Public Notice # 1 (released August 20, 2009), the FCC sought comments regarding the definition of broadband. While many of the comments received in response to that notice discussed speed as one of the defining characteristics of broadband, there was not a consensus regarding how speed should be defined. In addition to several comments which made no attempt to define speed,[1] a number of comments proposed that speed be defined in terms of the following modifiers: "peak" rate,[2] "advertised" rate,[3] "configured" rate,[4] "average" rate,[5] and "delivered" rate.[6]

The above terms have different value to the users of broadband services. "Peak," "advertised," and "configured" rates are note very useful to subscribers as they may not ever be experienced by an individual user accessing a broadband service, depending on the design of the access network. "Average" or "delivered" rates are more meaningful to the user, but they still may not ensure broadband performance appropriate for widely used applications. For the definition of a speed-related metric to be meaningful, it needs to be derived based on the requirements of the application classes that are broadly used or expected to grow significantly. We review these application classes and their requirements, and derive such a metric in Section 2 of this paper.

The definition of a meaningful speed metric generates another question. How is the performance of an access network to be evaluated against the metric both before and after the network is deployed? While measuring speed in a deployed network may be relatively simple, predicting it accurately prior to deployment can be difficult or impossible, depending on the network architecture. In many networks, the individual user speed varies significantly with the overall demand placed on the network by the pool of users served by it. This variation can be sensitive to minor changes in the distribution of user traffic, which can change unpredictably.

Network capacity, as opposed to speed, is independent of traffic loading. The capacity of a wireline access network[7] can generally be determined by inspection of the appropriate

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[1] Comments in response to NBP Public Notice # 1 from: Allied Fiber; ARRL; Covad; Internet2; OPASTCO; Qwest; Rural Cellular Association; TDI; and Time Warner Cable.

[2] Comments in response to NBP Public Notice # 1 from Qualcomm.

[3] Comments in response to NBP Public Notice # 1 from: FTTH Council; Hughes; NCTA; and Verizon.

[4] Comments in response to NBP Public Notice # 1 from Comcast.

[5] Comments in response to NBP Public Notice # 1 from Clearwire.

[6] Comments in response to NBP Public Notice # 1 from: CenturyLink; Frederick Maia; Free Press; Google; Native Public Media / National Congress of American Indians; Utopian Wireless; and Windstream.

[7] The capacity of a wireless access network can be considerably more difficult to determine than that of a wireline network. It is possible to estimate capacity for wireless networks, however, given some simplifying assumptions. That task is outside the scope of this paper.

network parameters. While speed cannot be determined directly from capacity, the relationship between capacity and the demand placed on a network is one of the factors determining whether the desired speeds will be supported. In that sense, capacity is an "enabler" of speed.

This White Paper generates projections for the capacity that will be required on a per-subscriber basis for consumer broadband access networks over the next few years. The requirements are based on the traffic projections in Cisco's Visual Network Index 2008-2013 with updates from Cisco [4, 5]. Cisco's projections are converted from continental totals to per-subscriber values than can then be applied to first, second, or middle-mile capacity requirements for access networks. As such, the values are directly applicable to the questions asked in NBP Public Notice # 11 [3] regarding the network components of broadband capacity.

The required capacity projections in this paper are updated relative to similar projections provided in a previous White Paper [2], which covered some of the same material. The differences between the earlier figures and the current ones are discussed, as well as the implications of those differences regarding the need to update projections on a regular basis as additional data becomes available.

2 Speed

There are many ways to define speed in an access network. Most service offerings advertise the maximum speed available on the connection, which may or may not be available when there are multiple users trying to access the network at the same time. In general, the speed experienced by an individual user on a broadband access network is likely to vary depending on how many other users are trying to use the same network, what they are trying to do, the architecture of the network, and other factors such as rate caps that may be placed on tiered service offerings by the access network service provider.

Even if we avoid marketing terms such as "advertised" or "maximum" speeds, defining speed in the most meaningful way is not trivial. As noted above, speed is not a fixed parameter – it varies based on the momentary demand being placed on the network. So while we can generate a single measurement of speed, for instance by using one of the many publicly available speed testing services,[8] that measurement tells us little about the overall performance of the connection over time.

Even if we take multiple measurements, we are faced with how to combine them into a meaningful metric. Take the example in Figure 1, which shows ten speed test results from a fictional access network.

[8] One example of a testing service is www.speedtest.net.

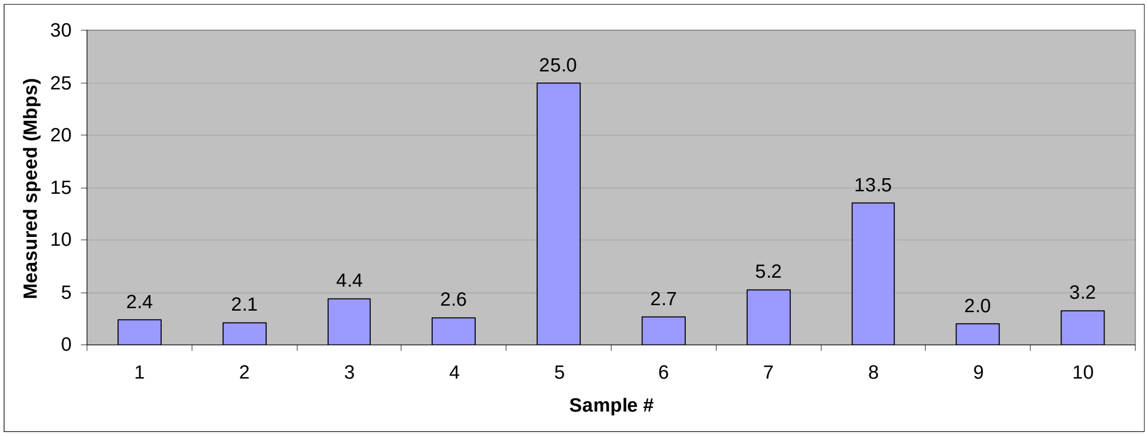


Figure 1 – Example speed test results

- The maximum sample is 25 Mbps. No other test result approaches the maximum sample value – in fact, only one other sample exceeds half the maximum value.
- The average of the ten samples is 6.3 Mbps. While taking the average is a straightforward approach, the resulting value in this case is higher than 80% of the speed test results.
- The median value is approximately 3.0 Mbps. Since the median by definition is exceeded by half the samples, we can expect to achieve this speed with about 50% probability.
- The minimum sample is 2.0 Mbps.

Which of the above choices, if any, provides the most appropriate description of network performance? Before we can generate a meaningful answer, we must understand the underlying requirements of the applications being used on the network.

2.1 Applications

Most of the data on current and forecasted application traffic volumes is taken from Cisco's Visual Networking Index 2008-2013 [4], updated by correspondence with Cisco [5].[9] Additional historical data comes from Cisco's VNI 2007-2012 [6], which contains estimates for traffic going back to 2006, and from other sources cited inline.

Figure 2 shows the estimated and projected consumer Internet traffic for North America for the years 2008-2013. The applications classes shown in the figure are discussed in the sub-sections below.

[9] The Cisco VNI 2008-2013, as published in June of 2009, contained inconsistent values for Consumer Internet traffic for North America in Table 3 and Tables 4-10. Cisco has since provided updated traffic values by email correspondence, and has indicated that they intend to update the published version of the VNI with the new values.

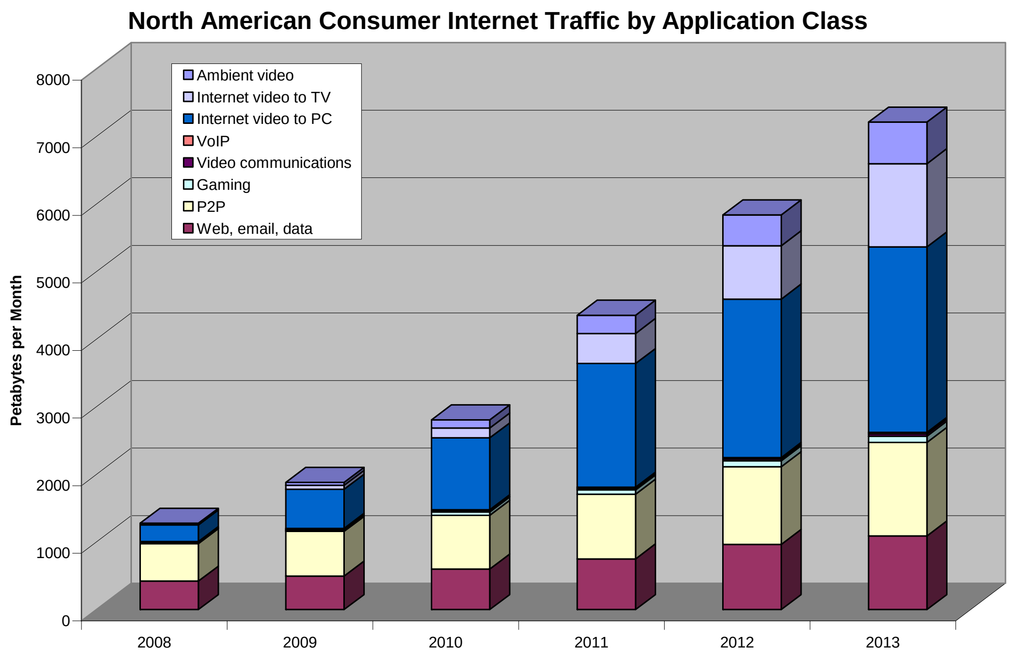


Figure 2 – North American consumer Internet traffic

2.1.1 Internet Video

Internet video is defined as video content which is accessed over the Internet via a subscriber's High Speed Internet Access (HSIA) service (as opposed to IPTV, which is sourced by a subscriber's service provider as a service separate from HSIA). While the best known examples of Internet video come from sites such as YouTube and Hulu, there are many different video sources, including broadcast and cable TV network web sites, social networking sites, movie delivery services, and educational web sites.

Internet video is widely considered to be the single largest factor in the growing requirement for bandwidth in broadband data services. Usage of the application has increased tenfold since 2006 and is expected to experience another sixfold increase by 2013. The growth of this application is changing traffic characteristics for HSIA in the following ways:

- It triggers a corresponding increase in raw volume. Current playout rates for Internet video range from approximately 300 kbps (YouTube standard definition) to approximately 2 Mbps ("HD" content from network web sites), for videos that may range from tens of seconds to hours in length. As true HD content at 5 to 6 Mbps becomes more widely available it will continue to drive volumes higher yet [7].
- When video is streamed for immediate playout, the playout rate is tied to a near-real time requirement for content delivery. Subject to the size of the receive buffer, viewing a video file in near-real time requires a data transfer rate at or above the playout rate, which must be sustained with little interruption for the duration of the video. If the transfer rate drops below the playout rate long

enough to starve the playout buffer, the video will "freeze" until the buffer refills. Repeated "freezes" can make streaming videos unwatchable.

- These video applications are driving higher usage statistics. As people increasingly turn to Internet video instead of traditional sources for video entertainment, the percentage of subscribers who are actively using the service at a given time grows.

Most sources classify Internet video differently from video content downloaded using peer-to-peer (P2P) applications for purposes of traffic analysis. The former is generally accessed via a client-server model, from sites such as YouTube, and watched in near-real time as it is being streamed (although some video content can be downloaded and stored for later viewing). Peer-to-peer traffic, discussed in Section 2.1.3, has different characteristics. Some applications such as Joost (discussed in Section 2.1.7), combine aspects of both of the above categories.

2.1.1.1 Video to PC and Video to TV

Most streaming video to date is watched directly on the user's PC. There is a growing market, however, for devices that allow Internet video to be played out on a television rather than a computer monitor [8, 9, 10]. As this market matures, it will reinforce the growth of Internet video by making the viewing experience more familiar, regardless of the source (*e.g.*, families watching movies or TV episodes via Internet video rather than broadcast or cable).

Cisco breaks Internet video into the separate categories of Video-to-PC and Video-to-TV. Video-to-TV content is identified as "film and television content" as opposed to the user-generated content common on sites like YouTube.

2.1.2 Ambient Video

Ambient Video is an emerging application class, first identified in this year's VNI. It consists of consumer generated content such as video from home security cameras, "nannycams," pet cameras, etc., which is forwarded from homes to other locations such as workplaces.

The rates required for ambient video vary, since video monitor sources of this type can be configured for low frame rates. Total volume is relatively low to date, but is expected to grow at a compound annual growth rate (CAGR) of 95% through 2013. As with Internet video, the application requires near-real time performance. Unlike Internet video, the traffic model is subscriber-to-subscriber (rather than client-to-server).

2.1.3 Video communications

While video communications (two-party video calls or video conferencing) is not yet widely adopted, it may be close to emerging as a significant application due to three enabling factors:

- Widespread broadband access,

- Widely available, inexpensive and easily installed webcams (frequently integrated in new laptops), and
- Free, widely available video communications features added on to VoIP and instant messaging applications.

Cisco projects that traffic for video communications will ramp up significantly in the 2013-2018 time frame. Once that growth does occur it will drive significant requirements for both symmetric and real time traffic volume.

The data transfer rate for a video conference connection is near constant when averaged over seconds, but may vary with the encoded video content when measured over a shorter period. The required rate, which is usually symmetric, varies from hundreds of kilobits to several megabits per second. Network performance issues, including drops below the momentary data transfer rate for periods as short as tens of milliseconds, can cause noticeable loss of audio and video quality.

2.1.4 Voice over IP (VoIP)

VoIP applications require constant, symmetric data transfer rates on the order of 100 kbps or less. VoIP has widespread usage but, due to its low bit rate, it drives a small percentage of overall demand. Its main impact on access networks is that its performance is very dependent on congestion. Even momentary congestion will cause noticeable loss in voice quality.

2.1.5 Gaming

Gaming applications have bursty data transfer requirements with rates on the order of 100 kbps. Like VoIP, gaming has stringent real time requirements and can suffer noticeable loss of quality due to momentary congestion.

2.1.6 Peer-to-Peer (P2P)

P2P applications and protocols, and the resulting traffic loads, have been extensively analyzed [11, 12, 13]. Estimates of the amount of traffic generated by P2P applications have ranged as high as almost 80% of all consumer traffic [14]. One of the defining characteristics of P2P traffic is its symmetry – for every peer receiving content over a P2P network, another peer must be sending. Even though newer P2P protocols such as BitTorrent get content from multiple peers to reduce the peak upload burden on any one host, the nature of the application dictates that upload and download traffic is balanced over the entirety of the network. This can strain networks that were designed on the premise of client-server applications and asymmetric traffic loads.

A second characteristic of P2P traffic is that the difference between peak and average daily load levels tends to be less than for other applications [14]. Since most P2P applications deal with non-real time traffic, some users presumably schedule P2P transfers for non-peak traffic periods so as to not interfere with their interactive applications.

While the raw volume of P2P traffic continues to grow, its percentage share is steadily shrinking. Estimated P2P traffic for 2008 was 43% of North American consumer traffic, down from 61% in 2006 (and down further still from the 80% estimated in 2003 [14]). At least part of this trend results from the growing dominance of non-P2P video as a percentage of Internet traffic.

2.1.7 P2P video services (Joost)

Relatively new services like Joost [15, 16] combine some of the challenging characteristics of both streaming video and P2P applications. Joost enables subscribers to download video, including feature-length TV programs and movies, for near-real time viewing (as well as storage and later viewing) using a P2P protocol. As with BitTorrent and other P2P protocols, each file is transferred in "chunks" from multiple peers.

This class of application combines the near-real time requirement of streaming video with the symmetric traffic loading of P2P applications. To the degree that it is adopted, it will affect access network requirements for both capacity and symmetry.

2.1.8 Web browsing, Email, Data

Traditional web browsing, email and other data applications will continue to represent a significant percentage of traffic volume. While speed is certainly a factor in the performance of these applications (especially file transfer), it is frequently less important than other factors such as latency [17].

2.1.9 Applications Summary

The applications described above can be grouped into three categories with regard to their sensitivity to varying speed:

- Near-real time, streaming applications (Video-to-PC, Video-to-TV, Ambient Video). These applications buffer seconds to minutes worth of received data, making them tolerant to short periods in which the data transfer rate drops below the playout rate. If the speed drops for long enough to starve the receive buffer, however, the video will "freeze."
- Real time, interactive applications (Video communications, VoIP, Gaming). The tolerance of these applications to loss of data rate is on the order of tens of milliseconds. The required downstream data rates for VoIP and gaming are below those for most streaming video applications, but the required rates for video communications are as high as or higher than streaming requirements. Required upstream rates for any of these applications can be as high as or higher than for the streaming applications.
- Non-real time applications (P2P, Web Browsing, Email, Data). While these applications all benefit from higher speeds, they are not affected (other than variation in wait time) by variable performance.

The first two categories (near-real time streaming and real time interactive) suffer degraded performance if the network does not deliver the required speed with a high probability. In the streaming category, the requirement may correspond to measured speed that meets or exceeds the data transfer speed on the order of 90% of the time. Real time applications may require measured results that meet data transfer requirements on the order of 99% of the time or better.[10]

The above discussion leads us to a general definition of "speed" that meets the most stringent requirements for consumer applications that enjoy widespread usage. We will refer to this definition as "sustainable speed," which is defined as: ***the speed which a user can achieve with very high (99%) probability.*** Applying this definition to the speed test results of Figure 1, the sustainable speed in that example is no more than 2.0 Mbps and may be significantly less.

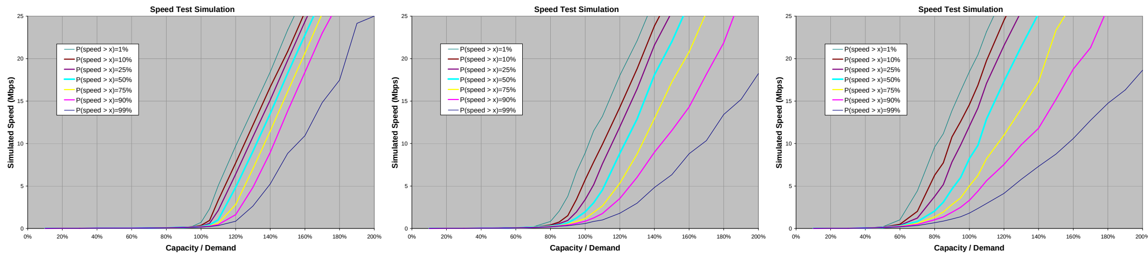
2.2 Predicting Speed

Now that we have reached a useful definition of speed, how do we determine its value in a given network? If the network is already deployed, that task is relatively straightforward. We can perform speed testing which, subject to the constraints of the tests, can provide an estimate of the sustainable speed available to a given user at a given time.

If the network is in the planning stages, predicting sustainable speed is much more difficult. Sustainable speed is dependent on more than just network design parameters, including architecture, link and node capacities, and traffic management design. It is also sensitive to a wide range of usage-related variables that may be largely unknown prior to deployment, including: total average traffic demand placed on the network; the distribution of that average demand between different users; and the mix of applications in use and the protocols over which they run. Even if these parameters can be approximated based on a history of deployments, they change over time, sometimes rapidly. For example, as ambient video emerges as a significant application class, it may change the demand distribution in the upstream direction (which to date has been dominated by a relatively small number of P2P users).

An example of the sensitivity of sustainable speed to small changes in usage parameters is shown in Figure 3. The plots in that figure show the results of three different series of simulations, all with identical parameters except for the shape of the demand distribution. In each case, the simulated network and the average traffic demand was identical, but varying the demand distribution generated significantly different results. (The reader is asked to suspend curiosity regarding details of the simulations, which will be revisited later in the paper. For the moment, the important point is the variation exhibited in the results.)

[10] How speed should be measured and how those measurements should be interpreted deserves its own white paper. For instance, most speed measurements are actually measuring throughput, or the time it takes to transfer a defined volume of test data. Variations in speed during the measurement period are usually averaged out. However, that subject is outside the scope of this paper, which (despite its emphasis to this point on speed) will focus on capacity.



a) α = 1.8 **b) α = 1.4** **c) α = 1.2**

Figure 3 – Simulated speed test results

In short, sustainable speed cannot be predicted based solely on network design parameters, and its sensitivity to small changes in usage parameters makes it difficult to predict at all.

3 Capacity

Compared to the above discussion of speed, definition of the capacity of a network is straightforward.[11] Capacity as a parameter is independent of traffic volume or the distribution of demand between users. It is strictly dependent on the design of the network itself.

The basic definition of access capacity as we will use it is: ***the total bandwidth available to the subscribers of an access network.*** The capacity can be expressed as an overall value summed over a group of subscribers, or pro rated per subscriber. The value can also be applied to a network as a whole or to a portion of a network. For example, the network in Figure 4 has three nodes, each of which serves 100 subscribers over a dedicated 20 Mbps link. The capacities for the network as a whole and for each node are summarized in Table 1.

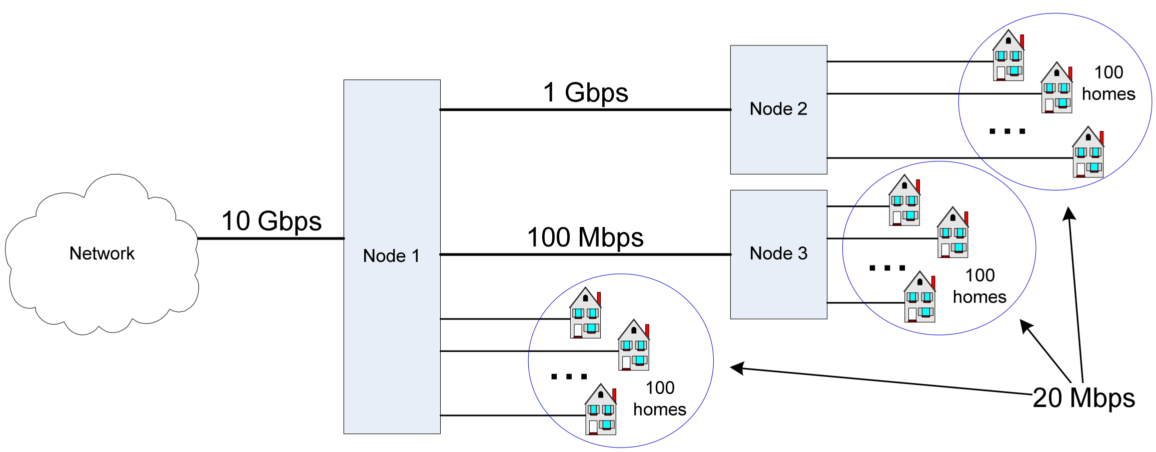


Figure 4 – Network capacity example

In each case in Figure 4, the capacity for a node is the minimum bandwidth available between that node and the core network. The pro rated capacity for the subscribers of a

[11] As noted earlier, determination of capacity for wireless networks is considerably more difficult than for wireline networks.

node is the minimum of the pro rated capacities on each link between the subscribers and the network. Note that the sum of the pro rated capacities for the subscribers on a node can be less than the capacity of the node itself, since the pro rated value considers all links north of the subscriber, including the links downstream of the node.

Table 1 – Capacities in Figure 4 example

Network Section	Overall Capacity	Capacity per Subscriber
Entire network	10 Gbps	Varies by node
Node 1	10 Gbps	20 Mbps
Node 2	1 Gbps	10 Mbps
Node 3	100 Mbps	1 Mbps

While capacity can be straightforward to determine, its usefulness depends on its ability to be related to speed or other network performance parameters. Unfortunately, we cannot relate capacity directly to sustainable speed with a simple equation – if we could, we could apply that equation directly to speed and bypass the entire discussion of capacity. We can, however, establish an approximate bounding relationship between capacity, demand, and speed which we can use to determine how much capacity is required to enable sustainable speeds.

3.1 Traffic Characteristics

Before getting into the details of the bounding relationship, a brief review of some of the characteristics of Internet traffic is in order.

3.1.1 Non-uniform usage

A common characteristic of Internet traffic is non-uniform demand across the subscriber population. As in many populations, a minority of subscribers consumes a majority of the measured traffic load. One study [14] indicated that 2.9% of subscribers (in a pool of over 100,000) accounted for over 40% of the traffic on the network, and that the top 20% of subscribers accounted for slightly over 80% of the traffic.

The concentration of demand in a small percentage of the subscriber population significantly increases the expected variance in demand in access networks, where the subscriber pool is smaller than in aggregation or core networks. In a network providing access to 100 subscribers, the usage characteristics of less than 20 households can be expected to dominate the traffic load.

3.1.2 Self-similar traffic

Another well documented characteristic of Internet traffic is self-similarity [18, 19]. One of the effects of self-similarity is fluctuations in momentary traffic load that exceed those predicted by models such as Poisson arrivals. Mori *et al.* [20] measured the skewness and marginal distributions of Internet traffic on a number of network links. The results show positively skewed distributions with momentary loads (summed and measured at 100 ms intervals) exceeding twice the mean rate in all measured traces.

3.2 Capacity, Demand, and Speed

To illustrate bounding relationship between capacity, demand, and speed, we return to the simulations first mentioned in Section 2.2. Figure 5 shows the results of a series of Monte Carlo simulations of individual speed test results across a resource shared by 500 users. The average demand is kept constant at 100 kbps per user, and the overall capacity of the shared resource is varied from one set of simulations to the next. Each set consists of 1000 simulations in which the demand placed by each user on the network is defined by a Pareto distribution with the shape parameter $\alpha = 1.2$. (This value generates the classic 80/20 distribution of demand mentioned in Section 3.1.1.) In each simulation, a random user runs a speed test that uses all the available capacity on the resource. The results are ordered and percentile curves are plotted in the figure.

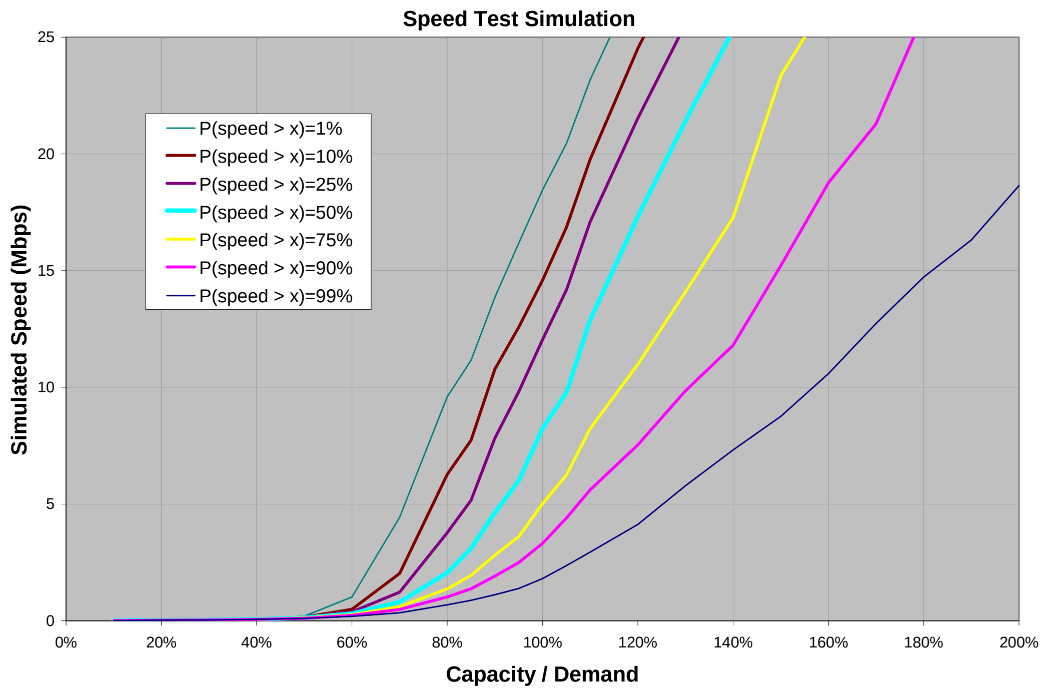


Figure 5 – Speed test simulation, α = 1.2

A quick inspection of Figure 5 reveals two obvious results. First, when network capacity is lower than demand (the left side of the chart), the network is congested and performance is minimal. Second, when network capacity exceeds demand by a sufficient margin (the right side of the chart), performance is excellent.

A third observation is less obvious: as capacity increases in the uncongested region of the chart, ***the increase in an individual user's speed performance is proportional to the increase in the overall capacity of the resource.*** This result has a multiplicative effect – if there are many users sharing a resource, the benefit of increasing the overall capacity of that resource is not divided among them – it increases the sustainable rate for each user by a significant fraction of the overall increase.

For the specific simulations documented in Figure 5, an increase in capacity from 120% to 180% of demand represents an increase of 30 Mbps in the shared resource. The corresponding increase in sustainable rate (using the 99% percentile point) is over 10

Mbps. If the effect was shared proportionally between all 500 users of the resource, the increase would be only 60 kbps!

It is important to note that the simulation described is not intended to be representative of any specific network, nor is it detailed enough to solve for a specific relationship between capacity, demand and speed in a realistic scenario. It makes no attempt, for instance, to simulate protocol behavior or traffic management techniques other than max-min fairness [21]. As noted earlier, actual demand distributions in deployed networks (while they may resemble Pareto in some respects) are largely unknown and subject to change over time.

While the above caveat reminds us that we cannot directly predict speed using capacity, the multiplicative effect of increases in shared capacity allows us to establish a bounding relationship which, while it may be conservative in that sustainable speeds may be higher than necessary, will not force the shared resource to be exorbitantly expensive. If we provide enough capacity margin relative to demand – that is, if we stay far enough towards the right side of charts like Figure 5 – we can expect that the shared capacity in the network will not be a limiting factor in providing sustainable speed at reasonable values.

3.3 Capacity Margin

The preceding paragraph begs the question – how much capacity margin should we provide relative to expected demand? There are two parts to the answer.

First, we must account for the ratio between average and momentary peaks in demand discussed in Section 3.1.2. Due to the self-similar nature of network traffic, this ratio (on the order of two to one, based on the data in [20]) should not change significantly over the range of population sizes encountered in access networks. A 2:1 margin over average demand to account for the burstiness of Internet traffic will not eliminate congestion, but it will minimize it.

Second, we must account for variation in the average demand across the user populations served by access nodes. As noted in Section 3.1.1, user demand is highly non-uniform and may follow a Pareto or similar distribution. While such distributions can show self-similar characteristics, user demand is also bounded in actual networks, either by physical network elements or by a rate cap imposed by the access network provider. Preliminary simulations indicate that rate caps tend to limit the self-similarity in the user distribution so that the resulting variance tends toward being inversely proportional to the size of the user population, with required margins ranging from about 1.5 (for larger access networks on the order of 1000 users) to as high as about 4 (for smaller access networks on the order of 50 users). Since the actual user distributions are not well known, however, we will use a simpler rule of thumb and scale the per-household averages by a factor of 2:1 to account for non-uniform demands. Note that this factor may be low relative to the actual variation in smaller networks.

When both margins are applied, the required capacity on an access network becomes four times the expected average traffic demand.

4 Traffic and Capacity Projections

The traffic volume values provided in [4] are monthly totals for consumer Internet traffic in North America. In this section we relate those figures to usage on a per-household basis in the belief that the resulting figures may provide some guidance for scaling shared capacity in access networks.

As a quick check on the source data, the total monthly volume reported by the Minnesota Internet Traffic Studies [22] for the US was from 1,200 to 1,800 Petabytes. This is in line with Cisco's estimate of 1279 Petabytes per month for consumer traffic in North America in 2008.

The monthly estimates and forecasts for North America Internet traffic by sub-segment for the years 2006 through 2012 are taken from different tables in [4, 5] and compiled in Table 2. This is the same data shown graphically in Figure 2.

Table 2 – North American consumer Internet traffic by application class

By Sub-Segment (PB per month)	2008	2009	2010	2011	2012	2013	CAGR 2008–2013
Web, email, data	421	494	599	750	964	1,089	21%
P2P	555	662	795	956	1,150	1,384	20%
Gaming	9	19	50	64	88	92	59%
Video communications	3	6	11	18	24	34	63%
VoIP	18	21	22	23	23	23	5%
Internet video to PC	246	579	1,063	1,830	2,345	2,744	62%
Internet video to TV	3	56	146	444	789	1,233	233%
Ambient video	22	45	120	271	456	614	95%
Totals	1279	1881	2807	4357	5839	7213	41%

The following discussion is based on 2008 figures. Based on US population estimates and the most recent census figures for persons per household [23], there were approximately 117 million households in the US. Approximately 55% of US adults had broadband Internet access and another 10% had dial-up access [24]. Assuming that the Pew survey did not include more than one person per household, we can infer a high correlation between personal and household Internet access since access is normally provided on a per-household basis. So, approximately 65 million households had broadband connections, which should account for the vast majority of consumer traffic (with broadband having 5.5 times the number of dialup connections at over 10 times the speed and longer average session times, we can safely assume that dialup volume was relatively minor).

From Table 2, total volume in 2008 was about 1279 Petabytes per month. Spreading 1279 Petabytes per month across 65 million households gives us a long term average (measured over days) volume of approximately 60 kbps per household.

Table 3 shows the above analysis applied to the data in Table 2. The broadband adoption rate for year 2008 is from [24]. The rate for 2009 is 4% higher than 2008 based on 3%

gains reported over 9 months, and the rate for 2010-2013 is extrapolated at a linear increase of 3% per year based on survey results in [24] indicating that the rate of broadband growth may be slowing.

Table 3 – Internet traffic long term average traffic per household

Estimated broadband adoption	2008	2009	2010	2011	2012	2013
No. of households (million)	117.5	118.6	119.8	120.9	122.1	123.3
Broadband adoption rate	55%	59%	62%	65%	68%	71%
No. of broadband households (million)	64.6	70.0	74.3	78.6	83.0	87.5
Traffic by Sub-Segment (kbps per household)						
Web, email, data	20.1	21.8	24.9	29.4	35.8	38.4
P2P	26.5	29.2	33.0	37.5	42.7	48.8
Gaming	0.43	0.84	2.08	2.51	3.27	3.24
Video communications	0.14	0.27	0.46	0.71	0.89	1.20
VoIP	0.86	0.93	0.91	0.90	0.86	0.81
Internet video to PC	11.8	25.5	44.2	71.8	87.2	96.7
Internet video to TV	0.14	2.47	6.07	17.43	29.33	43.47
Ambient video	1.05	1.99	4.99	10.64	16.95	21.65
Totals	61.0	83.0	116.6	171.0	217.0	254.3

The above data includes both upstream and downstream traffic averaged over a long period (greater than 24 hours). As is well documented [14, 25, 26], traffic volume exhibits a diurnal pattern reflecting user activity cycles. While business activity peaks during normal weekday office hours, consumer activity peaks during evening hours, with much less variation between weekdays and weekends. A diurnal pattern with similar peak times of day applies to different categories of traffic, although different application classes exhibit different excursions from the mean [14].

We use data from [14] to estimate upstream and downstream volumes during peak daily periods. Modeling the diurnal excursions from the mean as approximately symmetric,[12] the corresponding average loads during peak traffic hours can be estimated as

$$P = M\left(1 + \frac{r-1}{r+1}\right), \tag{1}$$

where: P = the average load during peak periods,
M = the long term average load, and
r = the diurnal max/min traffic ratio.

The same study provides upstream vs. downstream traffic ratios for traffic from different application classes. These values are incorporated for the year 2008 data in Table 4.

[12] This assumption of symmetry probably results in underestimation of the peak period averages. The diurnal patterns for consumer traffic in [14] look approximately symmetric, but those in [26] look like they exhibit positive skewness, which would make the peak period volumes somewhat higher than those calculated here.

Table 4 – Traffic during peak hours, 2008

Application class	Web	P2P	Video to PC	Video to TV	Ambient video	Other (1)	Total
Long term mean *M* (kbps)	20.1	26.5	11.8	0.14	1.05	1.43	61.0
Diurnal max/min *r* (2)	5	2	5	2	2	4	
Mean volume *P* (peak time)	33.5	35.4	19.6	0.2	1.4	2.29	92.3
Down/up ratio (3)	8	1	8	8	1	1	
% downstream	89%	50%	89%	89%	50%	50%	
Downstream (peak time)	29.8	17.7	17.4	0.2	0.7	1.1	66.9
Upstream (peak time)	3.7	17.7	2.2	0.0	0.7	1.1	25.4

Notes on Table 4:

1. The Other class includes the gaming, video communications, and VoIP sub-segments.
2. [14] states that the maximum to minimum diurnal load ratio is about 2 for P2P traffic and about 5 for Web browsing traffic. For this analysis, the Web browsing ratio is applied to interactive categories and the P2P ratio is applied to categories in which files can be scheduled for off-peak download. Video-to-PC, which consists primarily of shorter clips at lower bit rates, is places in the interactive category. Video-to-TV, which includes feature length films at high playout rates, is placed in the off-peak category. Ambient video is assumed to be less subject to variation due to the background nature of video monitoring. While all the sub-segments in the Other class are interactive, VoIP and video calling may be somewhat more distributed in time so the ratio applied is reduced slightly.
3. Downstream/upstream ratios in [14] are approximately 8 for client/server applications that primarily download data, and approximately 1 for symmetric applications. For this analysis, all video traffic except ambient video is assumed to follow the client/server model. Increased adoption of P2P video (*e.g.*, Joost) could push upstream rates higher.

Table 4 shows how values for traffic loading during peak usage times, as they would be measured over reasonably short time frames of several minutes, are derived. Totals for the same parameters are provided in Table 5 for the years covered by the current Cisco forecast. The same data is shown graphically, and broken out by application class, in Figure 6 and Figure 7.

Table 5 – Average traffic scaled per household during peak usage hours

Direction	2008	2009	2010	2011	2012	2013	CAGR 2008-2013
Down (kbps per household)	67	95	138	206	261	303	35%
Up (kbps per household)	25	32	42	57	71	83	27%

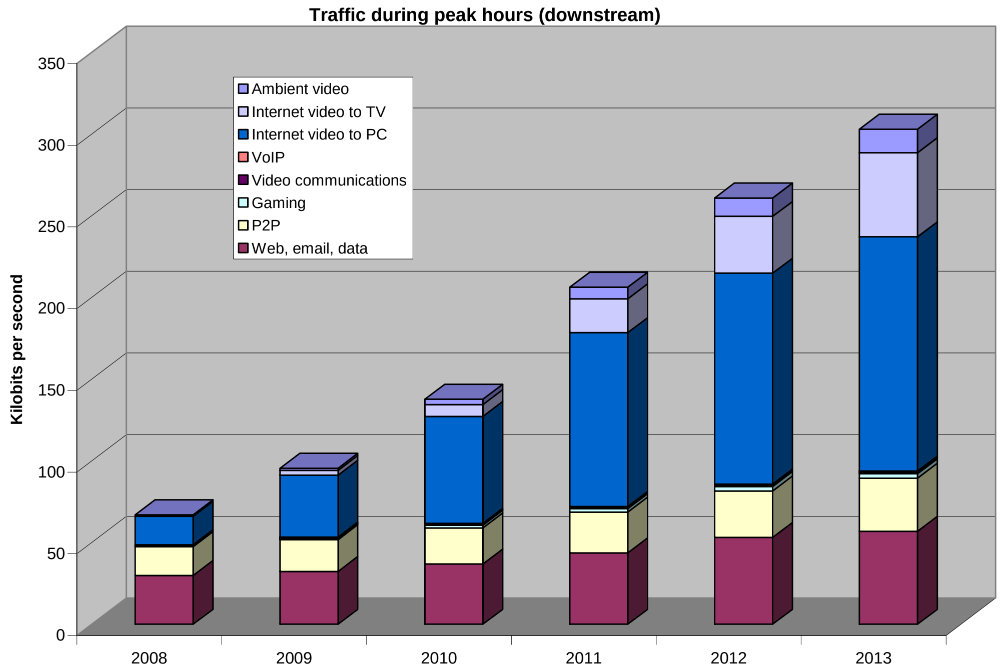


Figure 6 – Average traffic per household (peak hours, downstream)

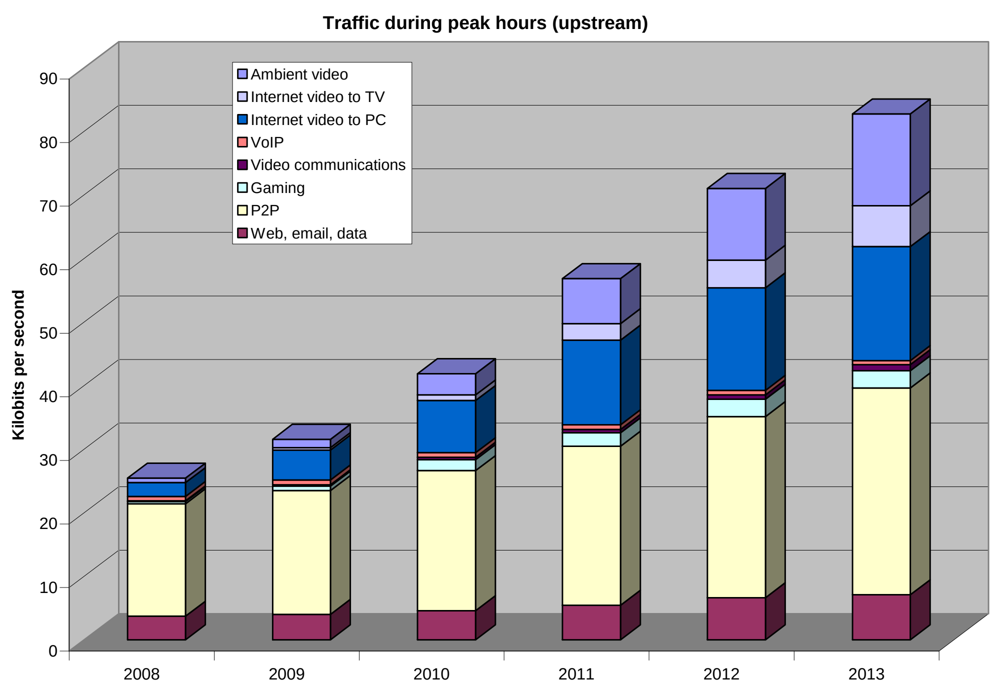


Figure 7 – Average traffic per household (peak hours, upstream)

At this point, we need to step back and list the accumulated *caveats* regarding the above numbers.

- Despite the scaling, the average values shown in Table 5, Figure 6 and Figure 7 are obviously not intended to be applied to individual households. Subject to the *caveats* below, they are scaling factors applicable (with the addition of appropriate margins) to large numbers of households in a given population.

- The extrapolation of future broadband adoption in this analysis may deviate significantly from the assumptions made by Cisco when generating their total volume forecasts. Differences in those extrapolations could have a significant impact on the per-household CAGR values.
- Finally, we need to remember that the forecast data from Cisco may not reflect actual future trends, considering the volatile history of the Internet [27]. While some characteristics of the Internet are relatively invariant, such as diurnal patterns and traffic self-similarity, other characteristics can change almost literally overnight. Rapid adoption of new applications, protocols or technologies could render the forecast obsolete, even in the relatively limited span that this forecast covers.
- Compared to the warnings listed above the following items seem almost trivial, but they are included for completeness. The analysis used forecast numbers for North America (including Canada) against population figures for the United States only, which inflated the per-household figures by an estimated 10%. Partly offsetting that, the forecast values do not include signaling traffic, acknowledged in [4] to add about 3% to overall volumes.

The per-household averages in Table 5 represent estimated and projected average traffic volumes. To generate required capacities from these volumes, we scale by the margins identified in Section 3.3. After performing the required scaling, we arrive at a current (2009) required capacity on the order of 400 kbps downstream and 150 kbps upstream per household for shared resources in the access network.

We use the CAGRs from Table 5 (and round up in increments of 100 kbps downstream and 50 kbps upstream) to generate projected capacity requirements for future years in Table 6. The values for year 2015 in the table should be considered tentative, since they extrapolate the CAGR beyond the forecast numbers provided by Cisco. Given the expense and time associated with deploying broadband infrastructure, however, a projected requirement that looks only three years into the future would result in deployments that are obsolete soon after their introduction.

Table 6 – Approximate required capacity/household for shared facilities in the access network

Direction	2009	2012	2015
Down (kbps per household)	400	1000	2400
Up (kbps per household)	150	300	550

As a final cautionary note, we compare the values in Table 6 with the corresponding values generated from Cisco's VNI for 2007-2012, published in 2008 [6]. The values generated using data from both years are shown in Table 7. As that table shows, updating of the source data by one year has had the result of generating a difference of nearly 2 to 1 downstream, and over 2 to 1 upstream, in the projected required capacities for year

2015. This difference underscores the importance of considering the 2015 values tentative, as well as the importance of revisiting and updating the data on a regular basis.

Table 7 – Comparison of projections from VNIs for 2008-2013 and 2007-2012

Source data	Direction	2009	2012	2015	CAGR
VNI 2008-2013	Down (kbps per household)	400	1000	2400	35%
	Up (kbps per household)	150	300	550	27%
VNI 2007-2012 **OUTDATED**	Down (kbps per household)	400	700	1400	26%
	Up (kbps per household)	150	150	200	11%

5 Summary

The different ways of defining "speed" in a broadband access network are examined in the context of how speed-related performance affects different classes of widely used consumer applications. Streaming video applications, which drive large and rapidly increasing traffic volumes, are found to be intolerant to excursions in the data transfer rate that go below the playout rate for extended periods. Interactive VoIP and video communications applications are the least tolerant of variable speed performance which may dip below the required rate. Based on the above application classes, we propose that "sustainable speed" be defined as the speed that is achievable with very high probability (on the order of 99%).

While sustainable speed can be measured in existing networks, it is nearly impossible to predict in the planning stages for access networks which rely on shared resources – which for practical purposes means virtually all access networks – due to its sensitivity to traffic demand parameters. In contrast, network capacity is a network parameter which is independent of demand and which can be determined during network planning. While there is not a specific relationship between capacity and sustainable speed that would not also be dependent on demand, we show that there is a bounding relationship such that if sufficient capacity plus scaling (relative to expected average demand) is provided in the shared resources, the network should support sustainable speeds in excess of the required values.

Once the necessary scaling to derive required capacity from average traffic has been established, the next step is to generate estimates of (and projections for) average traffic. We refine the data provided in Cisco's Visual Networking Index 2008-2013 [4, 5] to generate per-household averages for downstream and upstream traffic during peak daily demand hours, which occur in the evening for consumer traffic. These averages are then scaled to generate projected capacity requirements through the year 2012 (and tentative projections that extend through the year 2015).

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